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Sensors and Actuators B 105 (2005) 138–143

SENSORS AND ACTUATORS B CHEMICAL
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A surface plasmon resonance system for the measurement of glucose in aqueous solution

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Received 12 July 2003; received in revised form 16 April 2004; accepted 26 April 2004
Available online 22 December 2004

Abstract

In this paper, a surface plasmon resonance (SPR) system is proposed as an alternative approach for glucose measurement. The developed SPR system, which is based on wavelength interrogation technique, has a high detection resolution of 8.67×10^{-6} refractive index unit (RIU), equivalent to 6.23 mg/dL of glucose in water. The experimental results show that the proposed SPR system is capable of measuring the glucose at the concentration levels in physiological ranges, potentially leading to its further development towards a minimal-invasive glucose measurement of interstitial fluid.

Keywords: Surface plasmon resonance (SPR); Glucose measurement; Refractive index; Wavelength modulation

1. Introduction

Diabetes mellitus is a chronic disease and is a leading cause of death in many countries. The World Health Organization (WHO) forecasts the population of diabetes will reach 150 million worldwide by total 2025 [1]. A well-designed treatment for patient depends on frequent measurement of blood glucose level [2]. Therefore, they need to prick their finger to take the blood sample for conventional blood glucose measurement, which is a painful process and can raise other complications. The development of minimum or non-invasive blood glucose measurement techniques can avoid distressing blood harvest and improve living style for diabetic's patients. The paper proposed an optical configuration for measuring glucose level in water, which results are comparable to physiological glucose range in blood. The results encourage researchers to investigate non-pure mixture, interstitial fluid, measurement with SPR.

Surface plasmon resonance (SPR) technique based on an optical measurement approach is highly sensitive to the refractive index unit (RIU) of the sample on its surface. It has been widely adopted in analytical chemistry for detecting the presence and the concentration of chemical substances. Some researchers have demonstrated the feasibility of using SPR effect for glucose solution measurement [3,4]. However, the concentration of glucose studied cannot be compared with physiological blood glucose concentration. In this work, a SPR system based on the wavelength interrogation technique is proposed, for measuring refractive index (RI) changes associated with varying the constituent concentrations of glucose–water mixture corresponding to the physiological blood glucose ranging from 30 to 600 mg/dL. This SPR system is constructed by simple optics and electronic components, and it can be miniaturized for future portable monitoring device.

2. Theory

Surface plasmon resonance is a phenomenon that the charge-density oscillation induced by a p-polarized optical beam, which undergoes total internal reflection inside a metal-coated glass prism (Fig. 1). The metallic film is usually made of gold or silver and the optimum thickness suggested by the literature [5] is about 50 nm in order to provide better SPR coupling efficiency. During total internal reflection, electric fields of the incident photons leak into the metallic layer and the fields interact with the electrons confined in the metal film. The electron constellation of the metallic film will be excited by the incident photon energy

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0925-4005/$ – see front matter. © 2004 Published by Elsevier B.V.
doi:10.1016/j.snb.2004.04.088

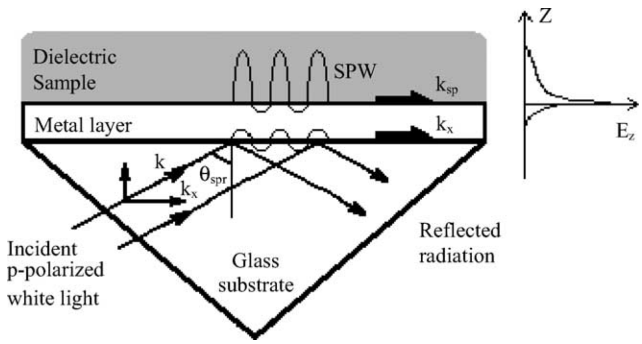

Fig. 1. Surface plasmon resonance is excited by totally internally reflected p-polarized light at a metal-coated interface when the momentum vector of the incident light in the plane of the surface (k_x) matches with the momentum vector of the surface plasmons in the metallic film (k_{sp}). The exponential behavior of the enhanced evanescent fields is also indicated on the right.

[5–8], if the condition for surface plasmon excitation is satisfied ($k_x = k_{sp}$), that is,

$$n_p \sin(\theta) = \sqrt{\frac{\varepsilon_{mr}\varepsilon_a}{\varepsilon_{mr} + \varepsilon_a}} \qquad (1)$$

where n_p is the refractive index of the prism ($n_p = \varepsilon_p^{1/2}$), θ the incident angle of the light beam to the interface of prism and metal film, and ε_{mr} and ε_a are the wavelength-dependent complex permittivity of the metallic film and dielectric sample, respectively.

From the Drude formula [9], the complex dielectric constant of metal ε_m and the resonant wavelength λ can be interrelated and written as

$$\varepsilon_m(\lambda) = \varepsilon_{mr} + i\varepsilon_{mi} = 1 - \frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c + i\lambda)} \qquad (2)$$

where ε_{mr} and ε_{mi} denote the real part and imaginary part of the dielectric constant of metal, respectively, λ_p denotes the plasma wavelength, λ_c denotes the collision wavelength, and λ denotes the resonant wavelength.

Under the excitation conditions, the energy of the incident light is transferred to charge-density waves (surface plasmons) and the intensity of the light reflected from the surface is reduced, which can be registered as a strong attenuation dip in the SPR curve. According to Eqs. (1) and (2), a small change in refractive index of sample solution on the metallic film will deviate the resonance conditions of SPR. The variation of the resonance condition corresponds to the shift of the light wavelength which causes the SPR effect providing that the incident angle of the light, θ is fixed. As refractive indices of materials are wavelength-dependent, so by taking differentiation of wavelength, λ, with respect to dielectric refractive index, n_a, the spectral sensitivity can be obtained.

$$s_{p\lambda} = \frac{d\lambda}{dn_a}\frac{\varepsilon_{mr}^2}{(n_a^3/2)\,|d\varepsilon_{mr}/d\lambda| + (\varepsilon_{mr} + n_a^2)\varepsilon_{mr}(dn_p/d\lambda)(n_a/n_p)} \qquad (3)$$

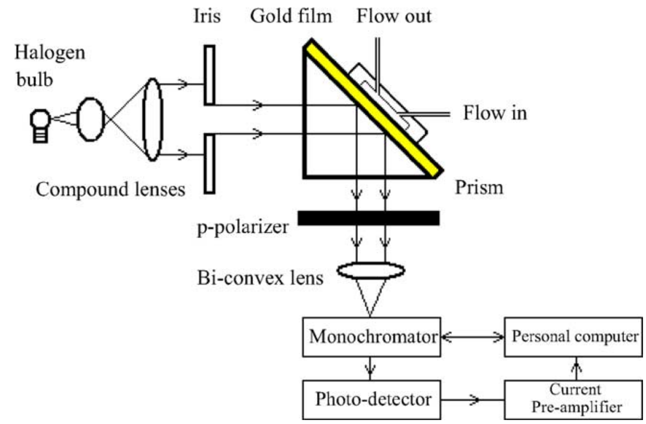

Fig. 2. Experimental scheme.

From Eq. (3), Homola and co-workers [4,9] reported that longer resonant wavelength gives higher spectral sensitivity and that the spectral sensitivity of SPR system should thus be improved at longer resonant wavelength.

3. Experimental setup

The configuration of the SPR system built for glucose level measurement is shown in Fig. 2. A commercial halogen bulb (manufactured by Philips, Type 7748XHP) serves as the broadband optical light source for exciting the surface plasmon wave. The emission spectrum, which is shown in Fig. 3, spans from about 400 to 1200 and 970 nm is the peak emission wavelength of the light source for a given silicon photo-detector. The emitted light is collimated through sets of compound lenses and an adjustable iris (up to 6 mm diameter). The collimated light is then impinged onto the bottom of a coupling prism at an angle greater than critical angle. The coupling prism is a 60° SF-18 prism coated with a ~50 nm thick gold film via DC sputtering. The reflected light is polarized by a polarizer and then focus into the entrance slit of the monochromator (Acton Research Corporation, SpectraPro-150). The decomposed signal light will be picked up by a silicon photo-detector (manufactured by Integrated Photomatrix, IPL10050) or germanium photo-detector which covers the wavelength region from 800 to 1800 nm (manufactured by Newport, 818IR), amplified by a current pre-amplifier (Standford Research System, SR570), and stored in a personal computer for further analysis.

4. Results and discussions

Two experiments of glucose measurements were carried out using the proposed system. In the first experiment, the initial resonant wavelength was tuned to 928 nm by adjusting the incident angle. Nine samples of glucose solution ranging from 30 to 600 mg/dL were prepared and kept at room temperature. The corresponding range of changes in RI is